Soil Solarization

A Nonpesticidal Method for Controlling Diseases, Nematodes, and Weeds

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Cover: Solarization of beds for organic vegetables. Weeds are controlled in the beds by solarization and in the furrows by cultivation.

SOIL SOLARIZATION

A Nonpesticidal Method for Controlling Diseases, Nematodes, and Weeds

Soilborne pests can be controlled in vegetable and fruit crops by preplant application of pesticides, including the fumigants methyl bromide, chloropicrin, and metam sodium. The use of these materials, however, is often undesirable due to their toxicity to animals and people, their residual toxicity in plants and soils, the complexity of soil treatment, and their high cost. Furthermore, restrictions on the use of soil-applied pesticides seem imminent as existing environmental legislation is implemented. As a result, there has been an increased emphasis on reduced-pesticide or nonpesticidal control methods.

Soil solarization is a nonpesticidal method of controlling soilborne pests by placing plastic sheets on moist soil during periods of high ambient temperature. The plastic sheets allow the sun's radiant energy to be trapped in the soil, heating the upper levels. Solarization during the hot summer months can increase soil temperature to levels that kill many disease-causing organisms (pathogens), nematodes, and weed seed and seedlings. It leaves no toxic residues and can be easily used on a small or large scale. Soil solarization also improves soil structure and increases the availability of nitrogen (N) and other essential plant nutrients.

Solarization is a simple, safe, and effective method that has been used with field, vegetable, and flower crops and in orchards, vineyards, greenhouses, gardens,

and landscapes in California for over 12 years. It can be combined with organic soil amendments or reduced rates of pesticide application for greater effectiveness. Large increases in plant growth, harvestable yield, and crop quality often occur in solarized soil and may continue for more than one growing season. The potential for using soil solarization to control diseases and pests in the warmer areas of California is excellent.

This publication is a brief introduction to soil solarization. For further information, consult your local Cooperative Extension Farm Advisor and the references listed in the bibliography at the end of this publication.

HOW TO SOLARIZE SOIL

Soil Preparation

Solarization is most effective when the plastic sheeting (tarp) is laid as close as possible to a smooth soil surface. Preparation of the soil begins by disking, rototilling, or turning the soil by hand to break up clods and then smoothing the soil surface. Remove any large rocks, weeds, or any other objects or debris that will raise or puncture the plastic.

Laying the Plastic

Plastic sheets may be laid by hand (see figure 1) or machine (see figure 2). The open edges of the plastic sheeting should be anchored to the soil by burying the edges in a shallow trench around the treated area. Plastic is laid either in complete coverage, where the entire field or area to be planted is treated, or strip coverage, where only beds or selected portions of the field are treated.

Complete coverage. In complete coverage, plastic sheeting is laid down to form a continuous surface over the entire field or area to be planted. The edges of the sheets may be joined with an ultraviolet (UV)-resistant glue or anchored by laying adjacent strips of plastic and burying both edges in soil (see figure 3). Anchoring the edges in the soil may be more cost effective initially than gluing the edges together but may also result in untreated soil being close to subsequently planted crops. The ends of the sheets should be held in place by burying them in the soil. If beds are formed after complete coverage, care must be taken to avoid deep tillage that could bring untreated soil to the surface. Complete coverage is recommended if the soil is heavily infested with pathogens, nematodes, or perennial weeds, since there is less chance of reinfestation by soil being moved to the plants through cultivation or furrow-applied irrigation water.

Strip coverage. In strip coverage, plastic is applied in strips over preformed beds (see figure 4). Strips should be a minimum of 30 inches (75 cm) wide; beds up to 5 feet (1.5 m) wide are preferred because several crop rows can be planted

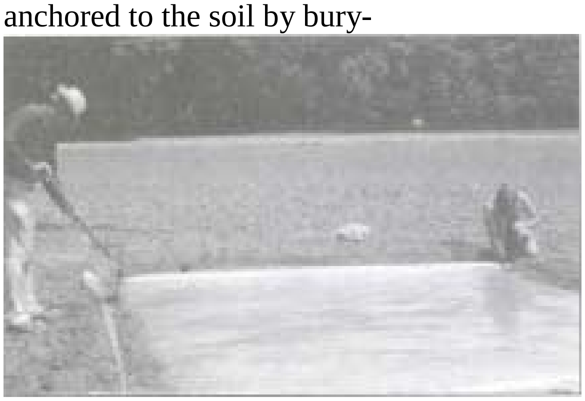

Figure 1. Applying clear 2 mil polyethylene tarps by hand Tarp is anchored to the soil by burying the edges.

Figure 2. Applying polyethylene tarps on 42-inch (105-cm) beds with a mechanical tarp layer.

Figure 3. Wide polyethylene strips laid together with soil covering both edges. The soil on top of the polyethylene is untreated and can reinfest treated soil after tarp removal

Figure 4. polyethylene applied by machine on 30-inch (76cm) beds. Strips narrower than these will not be as effective for pest control across the top of the bed.

per bed. In some cases, strip coverage may be more practical and economical than complete coverage because less plastic is needed and it is not necessary to join the edges of the plastic sheets together. Strip coverage effectively kills most pests and eliminates the need for deep cultivation after solarization. It is especially effective against weeds, since the furrows are cultivated. With strip coverage, however, longterm control of soil pathogens and nematodes may be lost because pests in the untreated soil in the rows between the strips can contaminate and reinfest treated areas.

Irrigation

Wet soil conducts heat better than dry soil and makes soil organisms more vulnerable to heat. The soil under the plastic sheets must be saturated to at least 70 percent of field capacity in the upper layers and moist to depths of 24 inches (60 cm) for soil solarization to be effective.

Soil may be irrigated either before or after the plastic sheets are laid. If the soil is irrigated beforehand, the plastic must be applied as soon as possible to avoid water loss; if heavy machinery is used to lay the plastic, however, the soil must be dry enough to avoid compaction. If the soil is to be irrigated after the plastic is laid, one or more hose or pipe outlets may be installed under one end of the plastic; drip lines may

Figure 5. Drip irrigation lines providing moisture under polyethylene during solarization of planting beds

be installed before the plastic is laid (see figure 5); or irrigation water may be run underneath the plastic in furrows or in the tracks made by tractor wheels if the plastic sheets were applied by machine. Fields treated by strip coverage can be irrigated by drip lines on or in the bed.

The soil does not usually need to be irrigated again during solarization, although if the soil is very light and sandy, or if the soil moisture is less than 50 percent of field capacity, it may be necessary to irrigate a second time. This will cool the soil, but because of the increased moisture the final temperatures will be greater.

Duration of Treatment

The plastic sheets should be left in place for 4 to 6 weeks to allow the soil to heat to the

greatest depth possible. To control the most resistant species, leave the plastic in place for 6 weeks. Experience has shown that there is little or no need to take the temperature of the soil. The greatest concern is to solarize the soil during a period of high solar radiation with little wind or cloud cover. Soil in the Central Valley can be solarized for 4 weeks any time from late May to September. In coastal areas the best time may be August to September or May to June, transitional periods when fog or wind may be at a minimum.

Removal of the Plastic and Planting

After solarization is complete, the plastic may be removed before planting. Or, the plastic may be left on the soil as a mulch for the following crop by transplanting plants through the plastic. Clear plastic may be painted white or silver to cool the soil and repel flying insect pests in the following crop. A disadvantage of leaving the plastic on the soil is that it may degrade and be difficult to clean up in the spring.

Treated soil can be planted immediately to a fall or winter crop or left fallow without the plastic until the next growing season. If the soil must be cultivated for planting, the cultivation must be shallow-less than 2 inches (5 cm)-to avoid moving viable weed seed to the surface.

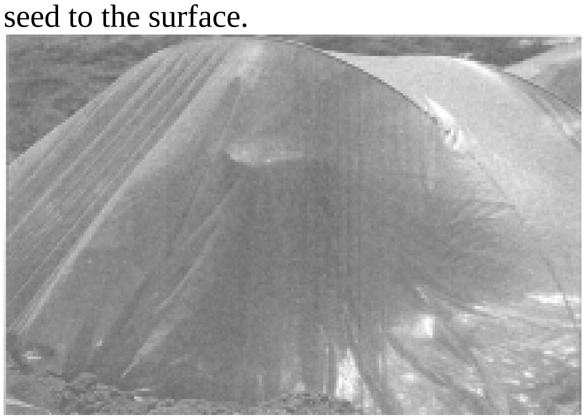

Figure 6. Containerized soil in tightly closed polytheylene tunnel being solarized bfore planting

Greenhouses

Solarization in greenhouses produces significantly higher soil temperatures than solarization in fields or gardens and can therefore be more effective in cooler weather. Greenhouse solarization is extensively used in southern Europe and Japan to control diseases of strawberries, tomatoes, eggplants, cucumbers, and other intensively managed crops.

The soil surface inside the greenhouse should be leveled and irrigated before being covered with plastic sheeting. Choose a time of year with maximum solar radiation. To maximize the transmission of light it may be advisable to wash the roof of the greenhouse before treatment. Once plastic is applied, the greenhouse should be tightly closed for 4 or more weeks to contain the heat.

Containerized Planting Media and Seedbeds

Soil solarization has been shown to be effective for disinfesting containerized soil and soil in cold frames (see figures 6 and 7). Soil temperatures should be monitored closely in this planting media to assure that temperatures are high enough to control pests. Materials can be solarized either in bags or flats covered with transparent plastic or in layers 3 to 9 inches (7.5-22.5 cm) wide sandwiched between two sheets of plastic. In warmer areas of California, soil inside black plastic sleeves can reach

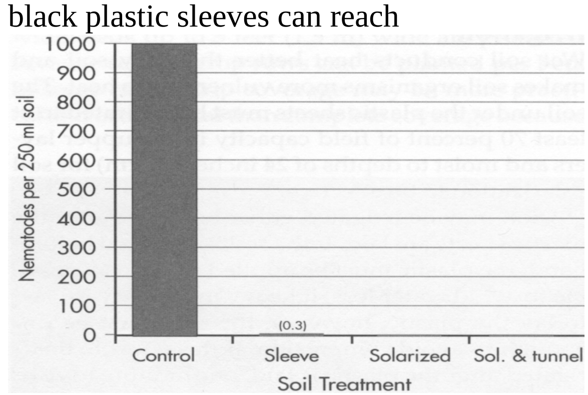

Figure 7. Effect of solarization on citrus nematode in containerized soil using plastic planting sleeves, solarization, or solatirization and plastic tunnel. All methods reduced the number of citrus nematodes compared to the untreated soil.

158°F (70°C) during solarization, equivalent to target temperatures for soil disinfestation by aerated steam. At these temperatures, soil is effectively solarized within 1 week. A double layer of plastic can increase soil temperatures by up to 50°F.

Soil temperatures can be monitored using simple soil thermometers inserted 4 to 6 inches (10-15 cm) into the soil mix or by using thermocouples and a digital reading logger. Temperatures can be monitored at different locations, but the duration should be lengthened to raise the temperature at the coolest location to the desired level.

Orchards and Vineyards

Soil solarization is most effective before or during establishment of new orchards or vineyards. It has been successfully used on a large scale to reduce Verticillium wilt symptoms in young pistachio orchards in California (see figure 8) and has also been successfully used in vineyards and in avocado, stone fruit, citrus, and olive orchards in the state.

In the orchard or vineyard, clear plastic is either laid by hand around the bases of individual trees or vines and connected to strips laid between the rows or laid in anchored strips and glued along the tree rows. For best results, begin solarization as soon as trees are planted. Partial shading by young trees does not prevent soil heating, nor does soil solarization appear to bother most young trees during treatment. However, solarizing certain species of trees, such as herbaceous perennials, avocado, and young *Prunus* trees, with clear plastic may result in plant damage, especially when trees are young. (The Prunus trees were killed by clear plastic but not by black film.)

In addition to killing soilborne pests, solarization of orchards and vineyards can greatly reduce the amount of water needed for irrigation and increase the growth, flowering, and/or fruit set of the trees. In large commercial orchards, the cost of postplant solarization should be compared to the benefits before making a treatment decision. Experience has shown that pests that are not eradicated by solarization may recolonize roots and soil, and pathogens and nematodes may survive in roots remaining in the soil. Periodic retreatment may be necessary.

Figure 8. Postplant soil solarization with clear polytheylene for control of Verticillium wilt in a pistachio orchard.

PLASTIC SHEETING

Clear vs. Colored Plastic

Transparent or clear plastic is most effective for solarization. Black plastic, often used for mulching, does not heat the soil as well as clear plastic. It can be used for solarization but its main effect is reducing weed growth. In areas where solarization is ineffective because of low solar radiation or a heavy infestation of weeds, black plastic may combine some solarization benefit with residual weed control. It can also be used for solarizing existing crops, for example, by disinfesting soil while establishing permanent tree or vine crops (see color plate 1).

Since soil temperatures are lower with black plastic, the treatment time must be lengthened for best results. Other colors of plastic, such as green or brown, which

allow some heating of the soil but not to the degree of clear plastic, require longer treatment times. These other colors of plastic give so much less effective solarization that they should probably only be used as mulch.

Types of Plastic

The thinner the plastic, the greater the heating will be. Polyethylene (PE) plastic 1 mil (0.001 inch [0.025 mm]) thick is efficient and economical but not very resistant to tearing by wind or puncture by animals. Users in windy areas should consider plastic sheets that are 1.5 to 2 mils (0.038-0.050 mm) thick. If holes or tears do occur in the plastic they should be patched with clear patching tape. Users are encouraged to select plastic sheeting containing ITV inhibiting additives that prevent sheets from becoming brittle and difficult to remove from the field and extend the life of the plastic. Plastic sheets laid by hand can often be used more than once for solarization, although if the plastic is dirty or dusty reuse is less effective.

Polyethylene sheets may be modified by an additive that enables them to absorb infrared (IR) radiation and improve their capacity to retain heat. Although these are available, they have not proven to be very effective. Colored plastic films are available that absorb light in the photosynthetic range to inhibit growth of weeds and at the same time heat the soil. These can be used for solarization but generally do not heat soil as well as transparent films.

There has been considerable interest in the development of high-density or "impermeable" plastic sheeting to better contain fumigant chemicals in soil. These plastics may also improve the effects of solarization by sealing in more heat and volatile compounds. However, these plastics are under development at this time, and information on benefits, sources, and prices is not currently available. Experimental work has also been done using a sprayable polymer as a replacement for plastic sheeting. Such a material would be easy to apply and less expensive to use, but to date suitable chemicals have not been found.

The use of a double layer of plastic with air space between the layers mimics the greenhouse effect and raises soil temperatures from 2° to 10°F higher than that obtained with a single layer. Using a double layer requires additional preparation time and expense but it may make soil solarization more feasible in areas with cooler climates.

Availability

For small applications in gardens, UV inhibiting plastic that is 1.5 to 4 mils (0.038-0.100 mm) thick can be purchased from nursery, hardware, or lumber establishments. These are sometimes called "drop cloths" and are used to catch paint drippings. For agricultural plantings, plastic can usually be purchased in rolls from 6 to 12 feet (1.8-3.6 m) wide and approximately 4,000 feet (1,200 m) long. Size will vary by source. Two suppliers of plastic are

- AEP Industries, Inc., 125 Phillips Ave., South Hackensack, NJ 07606; phone 1-800-999-2374 (wide range of colors and sizes including solarization and silver films)
- Polyon, Inc., Kibbutz Barkai, Israel 31860; U.S. Rep: PolyWest,1106 2nd St., Encinitas, CA 92024; phone (619) 943-7795; fax (619) 633-1265 (wide range of colors and sizes including solarization and IRT films)

Disposal

The disposal of plastic film after solarization presents an additional expense and involves consideration of environmental pollution. At present there is no program in California for recycling plastic used in soil solarization,

primarily due to the relatively low amount of plastic used. A few programs are operating in other states where a more constant supply of used agricultural plastic is available. In addition, soil adhering to used plastic makes recycling more costly. UV-treated plastics that are thicker than 4 mils (0.1 mm) may be usable for more than one season if handled carefully. Although most plastic has been put into landfills after use in solarization, some farmers store plastic at their own sites until recycling programs can be started.

Efforts have been made to develop a plastic film for solarization that would degrade completely after use in a suitable or predictable amount of time. These "biodegradable" or "photodegradable" plastics are not currently recommended for solarization. Photodegradable plastics degrade with exposure to UV light. Although they may be effective for solarization, the timed degradation (6 to 12 weeks) has not been uniformly effective. Also, the buried part of the plastic remains in the soil until it is brought to the surface with cultivation, leaving a source of pollution in the field.

RESULTS OF SOLARIZATION

Increased Soil Temperature

The heating effect of soil solarization is greatest at the surface of the soil and decreases with depth. The maximum temperature of soil solarized in the field is usually from 108° to 131°F (42° to 55°C) at a depth of 2 inches (5 cm) and from 90° to 99°F (32° to 37°C) at 18 inches (45 cm). Control of soil pests is usually best in the upper 4 to 12 inches (10-30 cm). Higher soil temperatures and deeper soil heating may be achieved inside greenhouses or by using a double layer of plastic sheeting. Soil solarized in greenhouses may reach 140°F (60°C) at a depth of 4 inches (10 cm) and 127°F (53°C) at 8 inches (20 cm). Soil solarized in black plastic nursery sleeves under a single or double layer of clear plastic can exceed 158°F (70°C).

Improved Soil Physical and Chemical Features

Solarization initiates changes in the physical and chemical features of soil that improve the growth and development of plants. It speeds up the breakdown of organic material in the soil, resulting in the release of soluble nutrients such as nitrogen (N03, NH4+), calcium (Ca++), magnesium (Mg++), potassium (K+), and fulvic acid, making them more available to plants. Improvements in soil tilth through soil aggregation are also observed.

Control of Pests

Repeated daily heating during solarization kills many plant pathogens, nematodes, and weed seed and seedlings. The heat also weakens many organisms that can withstand solarization, making them more vulnerable to heat-resistant fungi and bacteria that act as natural enemies. Changes in the soil chemistry during solarization may also kill or weaken some soil organisms.

Sensitivity to Solarization

Although many soil pests are killed at temperatures above 86° to 91°F (30° to 33°C), plant pathogens, weeds, and other soilbome organisms differ in their sensitivity to soil heating. Some pests that are difficult to control with soil fumigants are easily controlled by soil solarization (see table 1). Other pests are also affected but cannot be consistently controlled by solarization (see table 2). These may require additional control measures.

Fungi and bacteria. Solarization controls populations of many important soilborne fungal and bacterial plant pathogens, including *Verticillium dahliae*,

which causes *Verticillium* wilt in many crops; certain *Fusarium* spp. that cause *Fusarium* wilt in some crops; *Phytophthora cinnamomi*, which causes *Phytophthora* root rot; *Agrobacterium tumefaciens*, which causes crown gall disease; *Clavibacter michiganensis*, which causes tomato canker; and *Streptomyces scabies*, which causes potato scab (see table 1). Other fungi and bacteria are more difficult to control with solarization, such as certain hightemperature fungi in the genera *Macrophomina*, Fusarium, and *Pythium*, and the soilborne bacterium *Pseudomonas solanacearum* (see table 2).

Nematodes. Soil solarization can be used to control many species of nematodes (table 1). However, soil solarization is not always as effective in controlling nematodes as it is in controlling fungal disease and weeds because nematodes are relatively mobile and can recolonize soil rapidly. Nematode management may therefore require yearly treatment. Control by solarization is greatest in the upper 12 inches (30 cm) of the soil. Nematodes deeper in the soil profile may survive solarization (table 2) and damage plants with deep root Systems.

Nematode control by solarization is usually adequate to improve the growth of shallow-rooted, short-season plants. It is particularly useful for organic gardeners and home gardeners. Solarization may also be a beneficial addition to an integrated nematode control system. For example, excellent control of root knot nematode (*Meloidogyne incognita*) was obtained in the San Joaquin Valley by combining solarization with the application of composted chicken manure (Gamliel and Stapleton 1993).

Weeds. Soil solarization controls many annual and perennial weeds (table 1). While some weed species are very sensitive to soil solarization, others are moderately resistant and require optimum conditions (good soil moisture, tight-fitting plastic, and high radiation) for control (table 2).

Winter annual weeds seem to be especially sensitive to solarization, and control of winter annuals is often evident for more than one year following treatment. Soil solarization is especially effective in controlling weeds in fall-seeded crops such as onions, garlic, carrots (see color plate 2), broccoli and other brassica crops (see color plates 3A and 3B), and lettuce. White sweetclover (Melilotus alba) is one of the few winter annuals that is poorly controlled.

Although summer annual weeds are less temperature-sensitive than winter annuals, most summer annuals are relatively easily controlled by soil solarization. Control of purslane (Portulaca oleracea) and crabgrass (Digitaria sanguinalis) may be more difficult to achieve. If purslane is controlled, it is a good indicator that the soil has been adequately heated.

Solarization generally does not control perennial weeds as well as it controls annual weeds because perennials often have deeply buried underground vegetative structures such as roots and rhizomes that may resprout. Seed of bermudagrass (*Cynodon dactylon*), johnsongrass (*Sorghum halepense*), and field bindweed (*Convolvulus arvensis*) are controlled by solarization. Rhizomes of bermudagrass and johnsongrass may be controlled by solarization if they are not deeply buried. Solarization alone is not effective for the control of the rhizomes of field bindweed. Yellow nutsedge (*Cyperus esculentus*) is only partially controlled by soil

Table 1. Pathogens and pests controlled by soil solarization.

Fungi Scientific name	Disease caused (crop)
Didymella lycopersici	Didymello stem rot (tomato)
Fusarium oxysporum f. sp.	Fusarium wilt (cucumber)
conglutinans	Fusarium wilt (strawberry)
Fusarium oxysporom f. sp. fragariae	Fusarium wilt (tomato)
Fusarium oxysporum f. sp. lycopersici	Fusarium wilt (cotton)
Fusarium oxysporum f. sp. vasinfectum	club root (cruciferae)
Plosmodiophoro brassicae	pink root (onion)
Phoma terrestris	Phytophthora root rot (many crops)
Phytophthora cinnamomi	corky root (tomato)
Pyrenochaeta lycopersici	seed rot or seedling disease (many
Pythium ultimum, Pythium spp.	crops)
Pythium myrothecium	pod rot (peanut)
Rhizoctonia solani	seed rot or seedling disease (many
Sclerotinia minor	crops)
Sclerotium cepivorom	drop (lettuce)
Sclerotium rollsii	white rot (arlic and onions)
Thielaviopsis basicola	southern bight (many crops)
Verticillium dahliae	black root rot (many crops)
	Verticillum wilt (many crops)

Bacteria Scientific name	Disease caused (crop)
Agrobocterium tumefaciens	crown gall (many crops)
Clavibacter michiganensis	canker (tomato)
Streptomyces scabies	scab (potato)

Nematodes Scientific name	Common name
Criconemella xenoplax	ring nematode
Ditylenchus dipsaci	stem and bulb nematode
Globodera rostochiensis	potato cyst nematode
Helicotylenchus digonicus	spiral nematode
Heterodera schachtii	sugarbeet cyst nematode
Meliodogyne hapla	northern root knot nematode
Meliodogyne javanica	Javanese root knot nematode
Paratylenchus hamatus	pin nematode
Pratylenchus penetrans	lesion nematode
Pratylenchus thornei	lesion nematode
Pratylenchus vulnus	lesion nematode
Tylenchulus semipenetrans	citrus nematode
Xiphinema spp.	dagger nematode

Weeds Scientific name	Common name
Abutilon theophrasti	velvetleaf
Amoranthus albus	tumble pigweed
Amaranthus retroflexus	redroot pigweed
Amsinckia douglasiana	fiddleneck
Avena fatua	wild oat
Brossica nigra	black mustard
Capsella bursa-pastoris	shepherd's purse
Chenopodium album	lambsquarters
Claytonia perfoliata	minerslettuce
Convolvulus arvensis (seed)	field bindweed
Conyza canadensis	horseweed
Cynodon dactylon (seed)	bermudagrass
Digitaria sanguinalis	large crabgrass
Echinochloa crus-galli	barnyardgrass
Eleusine indica	goosegrass
Lamium amplexicaule	henbit
Malva parvillora	cheeseweed
Orobanche ramosa	branched broomrape
Oxalis pes-caprae	Bermuda buttercup
Poo annua	annual bluegrass
Portulaca oleracea	purslane
Senecio vulgaris	common groundsel
Sida spinosa	rickly sida
Solarium nigrum	lack nightshade
Solarium sarrochoides	hairy nightshade
Sonchus oleraceus	sowthistle
Sorghum halepense (seed)	johnsongross
Stelloria media	common chickweed
Trianthema portulacastrum	horse purslane
Xanthium strumarium	common cocklebur

Table 2. Pathogens or pests unpredictably controlled by soil solarization.

Fungi Scientific name	Disease caused (crop)
Fusarium oxysporum f. sp. pini	Fusarium wilt (pines)
Macrophomina phaseolina	charcoal rot (many crops)

Bacteria Scientific name	Disease caused (crop)
Psuedomonas solanacearum	bacterial wilt (several crops)

Nematodes Scientific name	Common name
Meloidogyne incognito	southern root knot nematode

Weeds Scientific name	Common name
Convolvulus ar venis	field bindweed
cynodon dactylon (plant)	(plant)
Cyperus esculentus	bermudagrass
Cyperus rotundus	(plant)
Eragrostis sp.	yellow nutsedge
Malva niceansis	purple nutsedge
Melilotus alba	lovegrass
Sorghum halepense (plant)	bull mallow
	white sweetdover
	johnsongrass (plant)

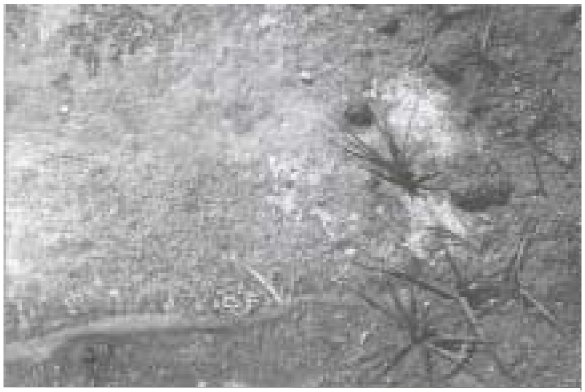

Figure 9. Yellow nutsedge is only partially controlled by solarization. It is controlled if it emerges under the plastic in the areas of high radiation, but it is not controlled if it emerges on the edge of plastic or on a cool side of the bed.

solarization (see figure 9). Purple nutsedge (*Cyperus rotundus*) is not significantly affected; marginal solarization has actually induced purple nutsedge to grow.

Encouragement of Beneficial Soil Organisms

Fortunately, although many soil pests are killed by soil solarization, many beneficial soil organisms are able to either survive solarization or recolonize the soil very quickly afterwards. Important among these beneficials are the mycorrhizal fungi and fungi and bacteria that parasitize plant pathogens and aid plant growth. The shift in the population in favor of these beneficials can make solarized soils more resistant to pathogens than nonsolarized or fumigated soil.

Earthworms. The effect of soil solarization on earthworms has.not received much attention, but it is thought that they retreat to lower depths and escape the effects of soil heating.

Fungi. Beneficial fungi, especially *Trichoderma*, *Talaromyces*, and *Aspergillus* spp., survive or even increase in solarized soil. Mycorrhizal fungi are more resistant to heat than most plant pathogenic fungi. Their populations may be decreased in the upper soil profile but studies have shown that this is not enough to reduce their colonization of host roots in solarized soil.

Bacteria. Populations of the beneficial bacteria *Bacillus* and *Pseudomonas* spp. are reduced during solarization but recolonize the soil rapidly afterward. Populations of *Rhizobium* spp., which fix nitrogen in root nodules of legumes, may be greatly reduced by solarization and should be reintroduced by inoculation of leguminous seed. Soilborne populations of other nitrifying bacteria are also reduced during solarization. Population levels of actinomycetes are not greatly affected by soil solarization. Many members of this group are known to be antagonistic to plant pathogenic fungi.

Increased Plant Growth

Plants often grow faster and produce both higher and better-quality yields when grown in solarized soil (see color plate 4 and figure 10). This can be attributed, in part, to improved disease and weed control; but increases in plant growth are still seen when soil apparently free of pests is solarized. A number of factors may be involved. First, minor or unknown pests may also be controlled. Second, the increase in soluble nutrients improves plant growth. Third, relatively greater populations of helpful soil microorganisms have been documented following solarization, and some of these, such as certain fluorescent pseudomonad and Bacillus bacteria, are known to be biological control agents.

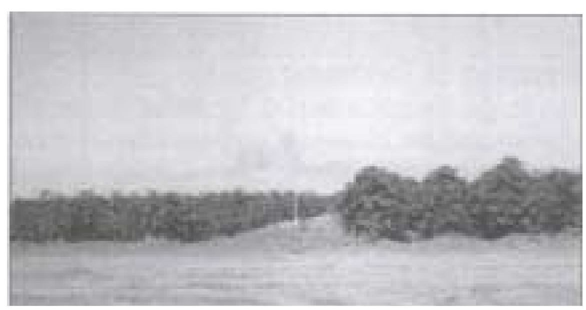

Figure 10. Growth responses of cotton in solarized (right) and unsolarized (left) soil

FACTORS THAT LIMIT EFFECTIVENESS OF SOLARIZATION

Location
Soil solarization is most effective in warm, sunny locations such as the Central Valley and desert valleys of California. It also has been used successfully, but less predictably, in the cooler coastal areas of California and in many cooler parts of North America during periods of highest air temperatures and clear skies. Greenhouse, nursery, and seedbed (containerized) media solarization are more effective in cooler climates than field solarization.

Weather
Highest soil temperatures occur when days are long, air temperatures are high, skies are clear, and there is no wind. The soil heating effect may be limited on cloudy days. Wind or air movement across the plastic will rapidly dissipate the trapped heat. Also, strong winds may lift or tear sheets.

Timing

The best time for solarization of soil in California is from June to August, although good results may be obtained in May and September, depending on weather and location. The heat peak in many areas of California is around July 15. To maximize production, soil solarization should be done during a period in crop rotations when fields are idle. For example, in the Imperial and Coachella Valleys, where summer temperatures are too hot for many crops, soil can be solarized during summer and planted during fall or winter.

Duration of Treatment
The longer the soil is heated, the better the control of pests will be. However, heating the soil longer than required for effective control (6 to 8 weeks) may be deleterious to the soil. Although some pest organisms are killed within 14 days, 4 to 6 weeks of treatment in full sun during the summer is recommended for field application. Solarization of containerized growth media and greenhouses may be done in a few days during the heat of summer. Some relatively heat-resistant organisms may require longer (up to 8 weeks) solarization for control. The combination of pesticides, fertilizers, and certain organic amendments with solarization may reduce the needed treatment time.

Soil Preparation
A smooth seedbed is ideal for solarization. Air pockets between the plastic and the soil greatly reduce soil heating. Solarization will be ineffective if the seedbed is not smooth and the plastic does not rest directly on the soil.

Soil Moisture Content
If the soil is too dry (less than 70 percent of field capacity), weed seed and pathogens may not imbibe enough water to make them vulnerable to the increased heat.

Soil Color
Dark soils absorb more solar radiation than lighter colored soils and reach higher temperatures during solarization. However, adding dark material, such as charcoal, to a light loam soil has only raised maximum temperatures 1° to 2°F. Organic material such as manure may give the same limited effect.

Orientation of Beds
The heating of soil in raised beds will be most uniform if the beds are oriented north to south rather than from east to west. More uniform heating gives better control of pests. Solarization is most effective when there is no slope or when the slope has a south or southwest exposure. Lower temperatures

and poor control of pests will occur on north-facing slopes (see figure 11).

Cultivation after Solarization

Cultivation deeper than 3 inches (7.5 cm) after soil solarization should be avoided because it may bring weed seed and pathogens to the upper soil layer, causing severe weed and disease problems (see figure 12).

Integrity of Plastic Sheeting

Holes or tears in the plastic will adversely affect solarization (see color plate 5). Animals and people should be prevented or discouraged from walking on or otherwise disturbing the plastic.

Figure 11. Bermudagrass growth on the cooler north side of a bed. Bermudagrass was controlled in the remainder of the solarized area. Note that the strawberries planted adjacent to the treated area are unaffected by solarization.

COMBINING SOLARIZATION WITH OTHER CONTROL METHODS

Combining soil solarization with pesticides, organic fertilizers, and biological control agents has led to improved control of pathogens, nematodes, and weeds and may be especially useful in cooler areas, against heat-tolerant organisms, or to increase the long-term benefits of solarization.

Chemical Controls

Low application rates of fungicides, fumigants, or herbicides have been successfully combined with soil solarization to achieve better pest control (see Hartz and others, 1993). The elevated temperatures seem to increase the activity of fungicides such as metam sodium, so lower rates may be applied. Solarization speeds up the disappearance of EPTC (Eptam) and vernolate, either by increasing their volatility or their degradation. Other chemicals, such as terbutryn or carbendazim, have slower degradation rates after solarization, possibly because of changes in the populations of soil microorganisms after solarization. Although such pesticides may be effective for longer periods than normal, care must be taken that they do not harm the next crop. Chemical controls may be applied either before or after solarization. A possible disadvantage of combining soil solarization with chemical control is that the chemical control may reduce the long-term benefits of solarization.

Amendments and Fertilizers

Solarization may also be combined with the application of crop residues, green and animal manures, and inorganic fertilizers. Many commercial users of solarization in California apply manures or other amendments to soil before laying the plastic. There is evidence that these materials release volatile compounds in the soil that kill pests and help stimulate the growth of beneficial soil organisms. For example, the southern root-knot nematode, which was incompletely controlled in lettuce by either solarization or application of composted chicken manure, was completely controlled by combining the two, resulting in a large yield increase (Gamliel and Stapleton 1993).

Biological Controls

Soil solarization has also been successfully combined with the fungal biological control

agents *Trichoderma hazianum* and *Talaromyces flavus,* which were added to the soil or planting material. In another integrated pest management strategy, clear plastic applied to planting rows in summer for solarization may be left in place and painted silver to control aphid-borne viral diseases in fall vegetable crops.

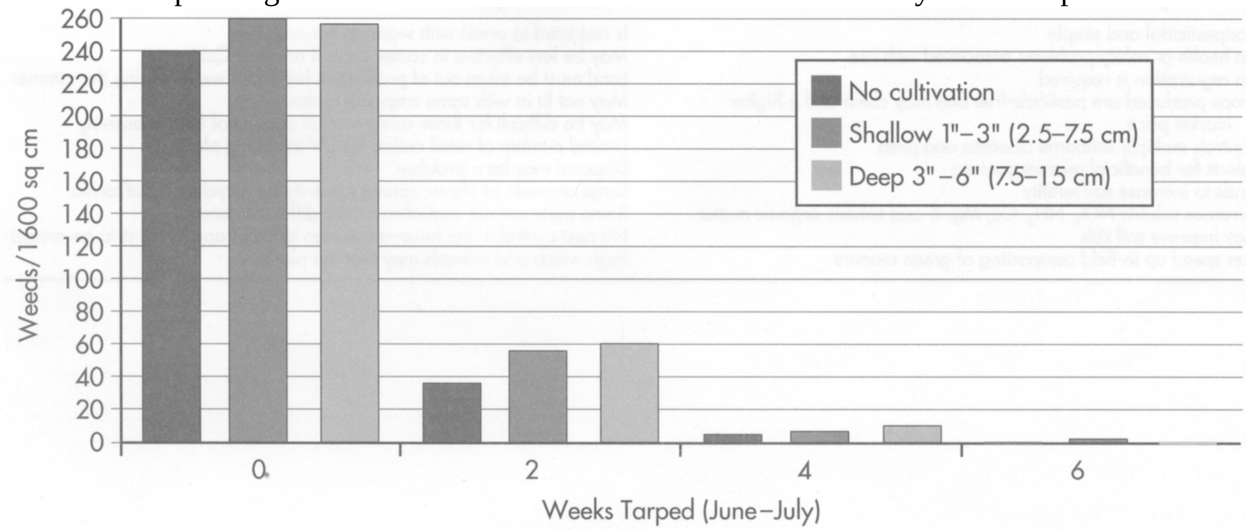

Figure 12. Effect of duration of solarization on the number of new weeds that emerge after cultivation at two different depths. Note that as duration of treatment is increased to 6 weeks, few weeds germinate from soil cultivated to a depth of 3 to 6 inches (7.5-15cm).

ECONOMICS OF SOLARIZATION

The cost of soil solarization depends on the thickness of the plastic used, the area of soil covered, the method of irrigation, and the method of plastic application, connection, and removal. These costs should be balanced against alternative methods of pest control, and in some cases should be viewed over a period of more than one year or growing season. In general, the greatest economic return from soil solarization will be obtained from high-value crops grown in soils infested with pathogens, nematodes, or weeds. Some of the factors that should be taken into consideration when deciding whether to solarize soil are summarized in table 3.

Advantages
Nonpesticidal and simple
No health or safety problems associated with use
No registration is required
Crops produced are pesticide-free and may command a higher market price
Controls multiple soilborne diseases and pests
Selects for beneficial microorganisms
Tends to increase soil fertility
Increases soluble N03, NH, Ca, Mg, K and soluble organic matter
May improve soil filth
Can speed up in-field composting of green manure
Disadvantages
Is restricted to areas with warm to hot summers
May be less effective in cooler coastal areas of California
Land must be taken out of production for 4 to 6 weeks during the summer
May not fit in with some cropping cycles
May be difficult for those using a small amount of land intensively
Limited number of retail outlets for UV-inhibiting plastics
Disposal may be a problem
Large amounts of plastic cannot currently be recycled in California
Some pests are not controlled or are difficult to control
No pest control in the furrows between strips (if applied in strip coverage)
High winds and animals may tear the plastic

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Plate 1

Plate 2

Plate 3A

Plate 3B

Plate 4

Plate 5

Plate 1. Postplant soil solarization in citrus using black polyethylene. **Plate 2.** Winter annual weed control with preplant soil solarization in carrots. **Plate 3A and 3B**. Winter annual weeds in nonsolarized (A) and solarized (B) broccoli beds. The solarized beds were covered with 1 mil polyethylene for 4 weekds in the summer before fall planting. **Plate 4**. Weeds controlled in broccoli with the standard herbicide (left) and with preplant solarization (right). Note the increased growth of brococoli in solarized soil. **Plate 5**. Purslane growing through a hole in a tarp. Holes or tears reduce the effectiveness of solarization at controlling weeds, nematodes, and pathogens.